# VARIABLE GRADIENT PERMANENT-MAGNET QUADRUPOLE LENSES*

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## Abstract

Rare earth (RE) permanent-magnet quadrupoles (PMQs) have been used for many applications in particle accelerators. They have the advantage over electromagnets of being lightweight and reliable. One difficulty associated with PMQs is that the quadrupole gradient is not easily adjusted. Over a certain range, the magnetization of RE magnets is a reversible function of temperature. We have developed a scheme to use this property to make variable gradient PMQs. The field gradient changes required for tuning are typically on the order of a few percent. For many RE magnets, this requires temperature changes of a few tens of degrees centigrade and is accomplished by actively heating or cooling the quadrupoles.

## Introduction

The Beam Experiments Aboard Rockets[1] project at Los Alamos has used permanent-magnet quadrupoles for the low-energy beam transport (LEBT) from the H$^-$ ion source to the radio-frequency quadrupole (RFQ) accelerator and for high-energy-beam transport (HEBT) from the RFQ to the beam neutralizer. These quads are quite convenient for a space-based application where all components must be lightweight and rugged. One disadvantage is that the fixed-focus nature of the lenses is overly restrictive. Adding actuators for mechanical adjustment[2-4] increases weight, complexity, and the likelihood of failure.

The LEBT is an area of particular difficulty. Here the beam transport is particularly sensitive to the degree of space-charge neutralization. With nonadaptive optics one cannot correct for nonideal plasma conditions in the ion source and LEBT.[5] The adjustment of the quadrupole strength required to compensate for the nonideal space-charge neutralization is typically on the order 1%. Furthermore, it is usually possible to manufacture magnets to within only a 1% tolerance of the design gradient.[4] As we will see below, the match into the RFQ is very sensitive to variations from the ideal in both of these areas.

We will show that appropriate adjustments to quadrupole gradients, without altering the field distribution, may be made by carefully controlling the temperature of the magnets. Sensitivity of RE magnets to temperature has traditionally been considered undesirable;[6] however, here we use it to our advantage.

## Quadrupole Design

The LEBT optical system is a closely spaced quadrupole triplet as shown in Fig. 1. Each quadrupole is made of a number of magnet discs. Each disc contains eight neodymium iron boron (NdFeB) blocks, as shown in Fig. 2, arranged to give a quadrupole field. The only other materials in the quads are aluminum in the magnet housing and nonmagnetic stainless steel fastners. The magnetic field gradient of each quad may be adjusted only by the addition of aluminum shims between the magnet blocks and the inner housing wall. Using this technique, the quadrupole gradient of each magnet may be adjusted to within approximately 1% of the design value. To adjust the shims, the entire triplet has to be dismantled.

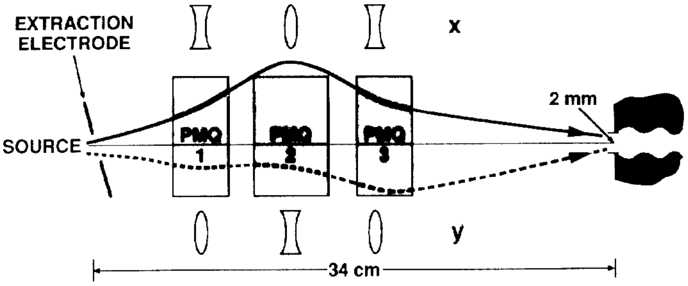

**Fig. 1.** Schematic of the LEBT transport from the source to the RFQ.

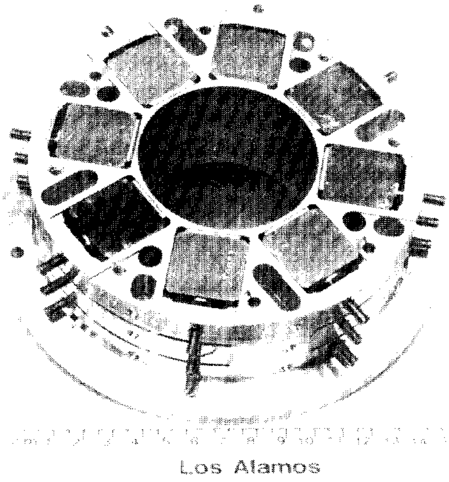

**Fig. 2.** Quadrupole Magnet. Each quadrupole is made up of a number of discs, and each disc contains eight NdFeB magnet blocks.

The nominal quadrupole gradients of the magnets are as follows:

| | | |
|---|---|---|
| PMQ #1 | 13.1 T/m | (3 discs) |
| PMQ #2 | 16.4 T/m | (4 discs) |
| PMQ #3 | 15.3 T/m | (3 discs) |

The LEBT system has been modeled using the TRACE-3D transport code.[7] The nominal design assumes 100% space-charge neutralization of the H$^-$ current as indicated in Fig. 3. The beam is emitted from a 4 × 1-mm$^2$ extraction slit with an extraction voltage of 30 kV. The X coordinate corresponds to a direction parallel to the short axis of the extraction slit, and the Y coordinate to the long axis. The typical H$^-$ current is 60 mA.

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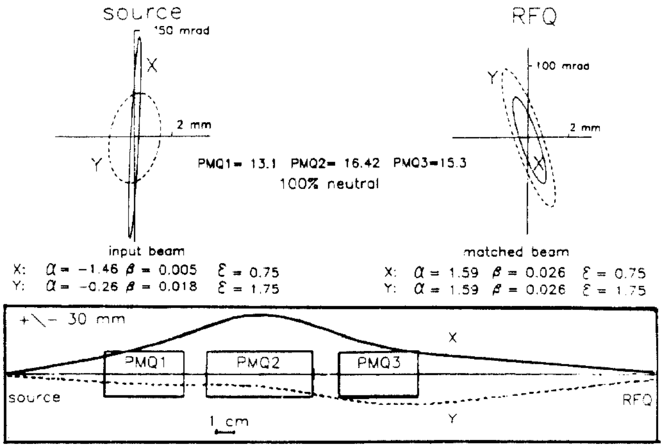

**Fig. 3.** The nominal LEBT design for a matched beam at the RFQ. The phase space ellipses in (X,X') and (Y,Y') are shown at the source and RFQ, along with associated Twiss parameters $\alpha, \beta$, and rms emittance $\varepsilon$ (cm-mrad). The PMQ gradients are in T/m.

The sensitivity of the match at the RFQ to magnet gradient errors is indicated in Fig. 4. In this case, the gradient of PMQ #2 has been increased by 1% over the nominal design value. This results in mismatch factors (m) of $m_x = 5.9$ in X and $m_y = 0.13$ in Y. A mismatched beam will oscillate about the ideal, or matched size, such that somewhere in the RFQ the beam will be a factor (1 + m) larger than the matched size.[7] In this case, the beam transmission through the RFQ would be reduced to less than 40%. Hence the ability to correct for such gradient errors is critical for the optimum performance of the accelerator.

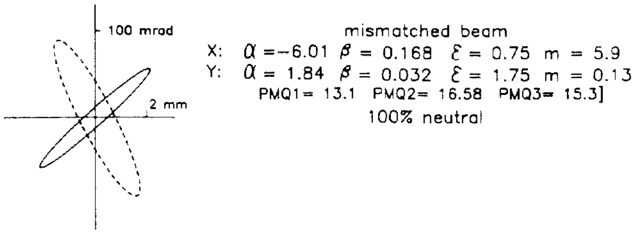

**Fig. 4.** Mismatched beam at RFQ as a reult of increasing the strength of PMQ2 by 1% over nominal The mismatch factors (m) are shown.

The situation is further complicated by the variably of the space-charge neutralization. The typical pressure in the transport region is $2 \times 10^{-5}$ torr of hydrogen. In addition, xenon gas is added to improve space-charge neutralization. The optimum partial pressure of xenon is typically $3 \times 10^{-5}$ torr. The effect of a xenon addition is indicated in the measured emittance plots at the RFQ entrance shown in Fig. 5. Without xenon, the beam is grossly mismatched at the RFQ entrance. The addition of xenon improves the match significantly. Because the quadrupoles cannot be readily fine tuned, the match can never be adjusted with precision. Figure 6 shows the transport calculation for a beam that is under-neutralized so that there is an effective current of -0.6 mA, that is, 1% under-neutralization. The mismatch factors are $m_x = 1.9$ and $m_y = 0.4$. This mismatch may be corrected by increasing the gradient of each PMQ as follows: PMQ + 2.5%, PMQ2 + 1.2%, and PMQ3 + 1.5%.

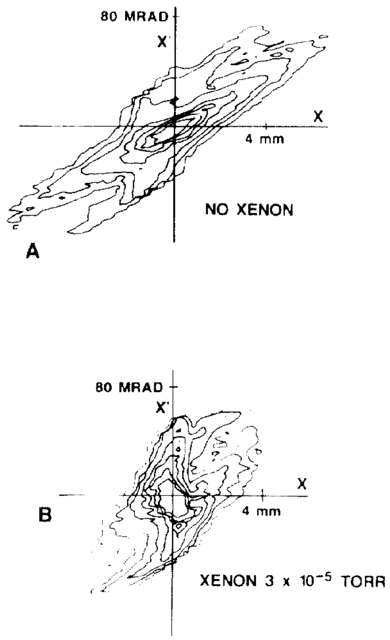

**Fig. 5.** Measured phase space (X,X') profiles at RFQ entrance, (A) without xenon and (B) with a xenon partial pressure of $3 \times 10^{-5}$ torr. Contour levels are 0.01, 0.05, 0.1, 0.2, 0,.3, 0.4, and 0.5 of peak signal.

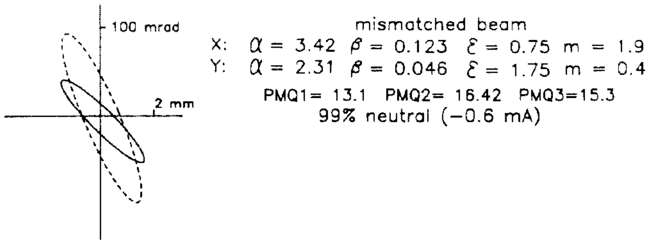

**Fig. 6.** Mismatched beam at RFQ as a result of under-neutralization. The net current is − 0.6 mA, corresponding to 99% neutralization.

## Gradient Adjustment by Temperature Control

There are several of types of RE magnet materials available with different temperature coefficients. The reversible temperature coefficient K is defined as follows:

$$K = 1/B_r(dB_r/dT)$$

where $B_r$ is the remanence of the material and T is the temperature. Typical values of K for some commercially available materials,[8] which have been temperature stabilized, are as follows:

| Material | K (%/°C) | Max. Revers. Temp (°C) |
|---|---|---|
| $Sm_2Co_{17}$ | −0.025 | 350 |
| $SmCo_5$ | −0.045 | 300 |
| NdFeB (H grade) | −0.1 | 150 |

Temperature stabilization of the material is necessary to avoid severe irreversible changes in $B_r$ when the magnets are heated. Stabilization can be achieved when the magnets are heated to temperatures beyond the desired working range.[6]

The gradient of a PMQ is linearly proportional to $B_r$. Therefore, varying the temperature of a PMQ will vary the quadrupole gradient without varying the field distribution, because there is no motion of magnet material. If one wishes to minimize the temperature excursion for a given gradient variation, the optimum choice of material is NdFeB.

Figure 7 shows the measured variation of an NdFeB PMQ gradient with temperature. The temperature of the quad was varied through a number of cycles from 4°C to 50°C by placing the quad in a water bath, whose temperature was known to ≃0.1°C. The magnets had been coated with an anti-corrosion coating by the manufacturer. The average value of K was found to be 0.09 ≃ 0.004%/°C.

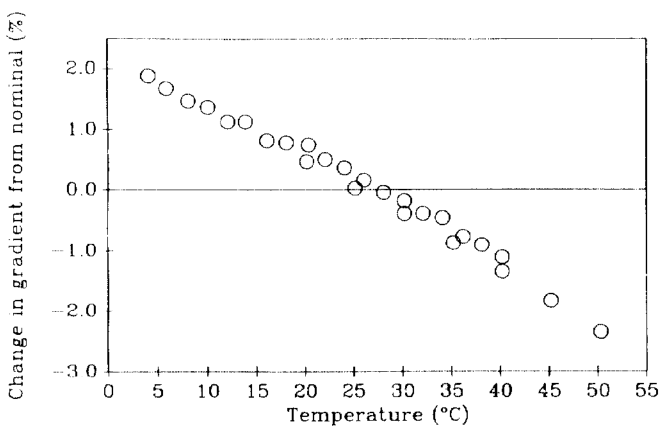

**Fig. 7.** Reversible change in quadrupole gradient vs temperature from nominal (25°C).

In a practical situation, it is desirable to have independent temperature control of each PMQ. Each PMQ should be thermally isolated. Heating/cooling of the PMQs may be achieved by wrapping coolant lines around the outside of each quad. The temperature of the coolant can be controlled by small heaters installed in the tubing. Such coolant is readily available on most accelerators, including the BEAR accelerator. Because the likely temperature changes of the PMQs are only a few tens of degrees centigrade, the addition of the extra coolant lines will not overburden existing cooling systems.

Heating the PMQs above room temperature is likely to be more convenient than cooling them. Therefore, it is desirable to construct quads that may be slightly stronger than desired at room temperature. In the case of NdFeB, one can reduce the quad strength by up to 11% in the range 25-145°C.

Unfortunately, even temperature-stabilized RE magnet alloys are subject to aging when held at elevated temperatures for long periods. Metal-bonded $Sm_2Co_{17}$ appears to be one of the materials least prone to aging; however, it still exhibits a flux loss of ≈1% when held at 100°C in dry air for 1000 hours.[9] Uncoated NdFeB alloy is subject to corrosion, such that at 60°C in 90% relative humidity atmosphere a 2% flux loss is noted in 300 hours.[6] Coatings are available that prevent corrosion in various situations.

## Acknowledgments

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